Watergy, Towards a Closed Greenhouse in Semi-arid Regions – Experiment with a Heat Exchanger

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Abstract

Water resources are diminishing in many (semi) arid regions, thus becoming a concern in the (near) future. Desalination of brackish or salt water can be a good solution to provide water for agriculture and human consumption. The Watergy project proposes an integrated system in which plants and fresh water are produced. The system is closed and air is being cooled during the day with a central heat exchanger in a chimney. Since this heat exchanger is a vital part for the functioning of the system, it was decided to test its characteristics such as heat transfer and air velocities in a controlled environment. A chimney was built with a heat exchanger installed inside with a surface of 11 m^2. Several experiments were conducted with varying layout of the heat exchanger, varying conditions and excitation signals. This paper describes the results of steady state situation with five baffles during heating and cooling. The measured air velocities are in the range of 0.72 - 0.6 m/s. The measured heat exchange coefficient is in the range of 25 - 28 W/m^{2}K. The efficiencies of all the presented experiments are in the range of 70 – 80%. The results of the experiments are compared to a simple physics based, steady state model that describes the convection, conduction and condensation processes. The model results are quite close to the experimental results; the maximum temperature deviation between model and observations on the water-side is 0.5°C (at 40°C) and on the air side 2.5°C. The accuracy of the model is sufficient to use it for design purposes and, later on, as a starting point for model based control of the greenhouse. Finally, the results of the experiments show that the heat transfer in the proposed design can be sufficient to cool and heat the Watergy greenhouse.

INTRODUCTION

Water resources are diminishing in many (semi) arid regions, thus becoming a concerning issue in the (near) future. Desalination of brackish or salt water can be a good solution to provide water for agriculture and human consumption. Since in most arid regions abundant sunshine is available, this is an obvious source of energy. Much research has been done in the development of solar stills and the integration of solar still and a greenhouse (Trombe and Foex, 1961; Maalej, 1991; Fath, 1994; Chaibi, 2000; Fath et al., 2002).

Most of the proposed systems do not (completely) integrate the two functions. The innovation proposed in the Watergy project is that it is an integrated system in which plants and fresh water are produced. The Watergy greenhouse uses the principle of a thermo-siphon, so the sun is the driving force for the airflow in the system, making it (almost) completely independent of external energy input (fans to circulate the air should not be needed). In literature, an overview of the Watergy system is available (Janssen et al., 2004; Jochum and Buchholz, 2004).

The Watergy project has several aims in different research areas, including understanding of solar thermal properties of the system, greenhouse (and building) heating and cooling, optimisation of crop production in the specific system, enhanced water efficiency in horticulture, model based control.

Description of the Watergy System

The basic shape of the Watergy greenhouse is a tunnel with in the centre a chimney (see Fig. 1). This chimney is closed at the top and has a double wall. It forms the heart of the system. A heat exchanger is installed in the central shaft to heat or cool the air. Furthermore, a lowered 'inner roof' is installed in the greenhouse over which (salt/ brackish) water can be sprayed.

The system functions as follows: during the day, the sun heats the air inside the greenhouse. As an effect, the air starts to rise through the outer duct of the chimney to the top of the tower. In the central shaft of the chimney the air is cooled with a water-air heat exchanger, causing the air to fall down and the whole process is repeated. The (brackish/ salt) water from the inner roof evaporates due to the solar energy and is transported upwards with the airflow. It condensates inside the cold heat exchanger in the tower and is therefore desalinated.

The warm water coming from the heat exchanger during the day is stored for heating of the greenhouse during the night. The direction of the airflow is the opposite of the day situation; from the bottom of the greenhouse, up through the central shaft and down again along the outer walls (see Fig. 1).

The Experiment

Since the heat exchanger in the central shaft of the chimney is a vital part for the functioning of the system, it was decided to test its characteristics in a controlled environment. The aim is to find the heat transfer and air velocities that can be achieved with natural ventilation in this specific setup. The results of the experiment are compared with a simple, physics based model.

From these results, conclusions can be drawn with respect to the heat transfer in the experiment, which can be used to estimate the maximum cooling capacity of the heat exchanger in the Watergy greenhouse.

MATERIALS AND METHODS

Experiment

In the experiments, a scaled and modified model of the real Watergy heat exchanger was used. A chimney containing the heat exchanger was built from wood and had a polystyrene insulation of 5 cm inside (see Fig. 3). The dimensions were approximately 0.4 by 1.0 m with a height of 3.7 m. The installed heat exchanger consisted of 3 mats of 96 vertical polypropylene capillaries (outer diameter 3.4 mm, inner is 2.4 mm), so the total heat-exchanging surface for the air is 11.4 m^2. To test the heat exchanger when it cooled the air, a tent was constructed around the chimney. Hot and humid air could be blown into the tent during the cooling experiments to keep the atmosphere constant.

The temperatures in the setup were measured with calibrated 4-wire PT100 sensors. Relative humidity was measured according to the wet-dry bulb method. The water flow was measured with a paddle wheel flow meter (accuracy 1% of measured value). The air velocities inside the chimney were measured with an Enotemp® acoustic sensor. This device was able to measure airflow with a resolution of 1 mm/s ±4mm/s.

Several experiments were conducted with a varying layout of the heat exchanger (number of baffles), varying conditions (heating and cooling) and varying excitation signals (steady state situations and step response and Random Binary Signals of the water flow). This paper describes the results of steady state and step response of the heat exchanger with five baffles during air heating and cooling.

Model

The process of heat transfer between water and air in the heat exchanger is modelled in a physical model. The model is deliberately kept simple, describing the main processes, being convection, conduction and condensation; radiation is neglected. Fig. 2 shows the principles in the heat exchanger, given a situation in which the air is warmer than the water. The model describes the transfer processes in time and space with differential equations for four balances; the moisture mass balance and the heat balance of the water, air and capillaries.

1. Air. Two heat fluxes are presented in the air; convection from the air to the solid capillaries (Q_{as}) and transport of energy by the airflow (Q_{aa}).

$$\mathrm{Q}_{aa} = \Phi_{v,a}\rho_{\mathrm{a,in}}\mathrm{C}_{\mathrm{p,a}}\left(\mathrm{T}_{\mathrm{a,in}} - \mathrm{T}_{\mathrm{a,out}}\right) \tag{1}$$

$$\mathrm{Q}_{as} = \alpha_{as}A_{as}\left(T_a - T_s\right) \tag{2}$$

Where $\Phi_{v,a}$ [m^3/s] is the airflow, α_{as} [W/m^{2}K] the heat transfer coefficient from air to the capillary, A_{as} [m^2] the heat exchanging surface T_a [K] is the temperature of the air and T_s [K] is the temperature of the solid capillaries (at the end of the paper a nomenclature is included).

The discretised average air temperature over a section is given by:

$$V_a\rho_{a,in}C_{p,a}\frac{dT}{dt} = \mathrm{Q}_{\mathrm{aa}} - \mathrm{Q}_{as}$$

$$\Rightarrow T_a\left(t+\Delta t\right) = T_a\left(t\right) + \left(\mathrm{Q}_{\mathrm{aa}} - \mathrm{Q}_{as}\right)\frac{\Delta \mathrm{t}}{V_a\rho_{a,in}C_{p,a}} \tag{3}$$

2. Water. The heat transport by the water is given by:

$$Q_{ll} = \Phi_{v,l}\rho_l C_{p,l}\left(T_{l,in} - T_{l,out}\right) \tag{4}$$

$$Q_{sl} = \alpha_{ls}A_{ls}\left(T_s - T_l\right) \tag{5}$$

Where Q_{ll} [W] is the heat flux due to the water flow and Q_{sl} [W] is the heat flux from the capillary wall to the water. The discretised average water temperature (T_l [K]) is given by:

$$T_l\left(t+\Delta t\right) = T_l\left(t\right) + \left(Q_{ll} + Q_{sl}\right)\frac{\Delta t}{V_l\rho_l C_{p,l}} \tag{6}$$

3. Condensation. As with air, there is energy transport by the airflow. The amount of water vapor that condensates on the capillaries (M [kg s^{-1}]) depends on the difference in vapor content (C [kg moisture/kg dry air]) and k, the mass transfer coefficient.

$$M_{aa} = \Phi_{v,a}\left(C_{in} - C_{out}\right) \tag{7}$$

$$M_{as} = A_{as}k\left(C_a - C_s\right) \tag{8}$$

The spatially averaged, time discretised, amount of moisture in the air (C_a [kg H_2O/kg dry air]) is given by:

$$C_a\left(t+\Delta t\right) = C_a\left(t\right) + \left(M_{aa} - M_{as}\right)\frac{\Delta t}{V_a} \tag{9}$$

4. Capillaries. The capillaries separate the water from the air. Since the capillaries are made of plastic, they will conduct (a small amount) of energy in the vertical direction (see figure 3). The amount of heat conduction (Q_{ss} [W]) depends on the temperature in the previous and next compartment (T_{s1} and T_{s2} [°C]) and the distance between the compartments (dx [m]). Another source of heat is condensation; when the moisture condenses the heat of vaporization (r [J/kg$_{\mathrm{water}}$]) is gained M_{as} is the amount of condensing water [kg/s].

$$Q_{ss} = \frac{\lambda_s A_s}{dx}\left(T_{s1} - T_{s2}\right) \tag{10}$$

$$Q_{as,condens} = r\,M_{as} \tag{11}$$

The total heat balance of the capillaries is given by:

$$T_s(t+\Delta t) = T_s(t) + Q_{as} - Q_{sl} + Q_{ss} + Q_{as,condens}\,\frac{\Delta t}{V_s \rho_s C_{p,s}} \tag{12}$$

The equations above are simulated in Matlab®.

RESULTS AND DISCUSSION

Results of the Experiments

1. Airflow. In the experiments, the air velocity is measured at one specific spot and ranges from 0.72 – 0.6 m/s (Table 1). From this velocity, the airflow has to be calculated. To this end, the overall heat balance is used. Since all other variables are known, it is possible to calculate the airflow using the equation given below (in steady state in a situation without condensation):

Energy loss air = Energy gain water

$$\Phi_{v,a}\rho_{a,in}C_{p,a}\left(T_{a,in} - T_{a,out}\right) = \Phi_{v,l}\rho_{l,in}C_{p,l}\left(T_{l,out} - T_{l,in}\right)$$

$$\Leftrightarrow \Phi_{v,a} = \frac{\Phi_{v,l}\rho_{l,in}C_{p,l}\left(T_{l,out} - T_{l,in}\right)}{\rho_{a,in}C_{p,a}\left(T_{a,in} - T_{a,out}\right)} \tag{13}$$

The average air velocity calculated from the heat balance is around 0.43 m/s. There seems to be a maximum value for the absolute air velocity. As can be seen in the data (see: Table 1), the airflow only slowly increases with increasing temperature difference in ingoing and outgoing air (which is the driving force). This suggests that the air pressure drop over the heat exchanger increases fast with rising airflows.

2. Heat Transfer Coefficient. The heat transfer coefficient is a good indication of how well a heat exchanger works. The overall heat transfer coefficient from the air to the water (α_{tot} [W/m^{2}K]) can be calculated from the experimental results. In a steady state situation (no heat storage) this can be done with the heat balance of the air side of the heat exchanger:

Energy in = Energy out

$$\Phi_{v,a}\rho_{a,in}C_{p,a}T_{a,in} = \theta_{v,a}\rho_{a,in}C_{p,a}T_{a,out} + \alpha_{tot}A_{tot}\left(T_a - T_l\right)$$

$$\alpha_{tot} = \frac{\Phi_{v,a}\rho_{a,in}C_{p,a}T_{a,in} - \Phi_{v,a}\rho_{a,in}C_{p,a}T_{a,out}}{A_{as}\left(T_a - T_l\right)} \tag{14}$$

Obviously, this relation is only valid for the case that no other heat losses occur other than the transport of heat from water in the capillary to the air. Table 1 gives the experimental heat transfer coefficients that were measured. If condensation occurs, this effect is also included in α_{tot}, which is something to keep in mind when comparing the results. The condensation during the cooling experiment seems to have raised the heat transfer coefficient slightly compared to the same situation in the heating case (α_{tot} = 27.7 vs. 25.5 W/m^{2}K).

3. Efficiency. A natural way of comparing different types of heat exchangers is the efficiency, defined as:

$$\eta = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}} \cdot 100\%$$

The efficiency can be calculated for both the air as the water side of the heat exchanger. Since the heat exchanger is used to heat or cool the air, the efficiency of the air side has been calculated:

$$\eta = \frac{\left(T_{a,in} - T_{a,out}\right)}{\left(T_{a,in} - T_{l,in}\right)} * 100\% \text{ (for cooling the air)} \qquad (15)$$

The efficiencies of all the presented experiments are in the range of 70 – 80% (see Table 1), which is a promising result. If the heat exchanger in the actual Watergy greenhouse has a comparable efficiency, it is probably capable of cooling the greenhouse at a sufficient rate (Jochum and Buchholz, 2004).

Results of the Model

The model was run with the same inputs as were used in the (steady state) experiments, to be able to compare them. Table 2 shows the results of the model simulations. The temperatures of the out flowing water are in accordance with the results calculated by the model. The maximum deviation is 0.5°C (at 40°C). The prediction of the air temperature by the model is slightly worse; maximum deviation is 2.5°C (which is around 6%). The air temperatures calculated by the model are all lower than the measured temperatures. Apparently, the model underestimates the heat transfer slightly.

Since the model estimates the behaviour of the heat exchanger within acceptable boundaries, it can be used for the design of similar types of heat exchangers. Until now, the model has only been used in a steady state situation, since our aim was to use it for design purposes. For our application, dynamic simulations are not needed, due to the high time constants of the greenhouse compared to the heat exchanger.

Earlier simulations of the whole Watergy system showed that airflows in the chimney of around 1 m/s should be enough to cool the greenhouse sufficiently and gain water by condensation. The air velocities found in these experiments look very promising; with a slightly improved design it seems possible to run the Watergy system without any fans for air circulation. If a fan turns out to be needed, probably the best choice would be an auxiliary (low power) fan, which is enough to circulate the air but will still be energy friendly

A point of further research is the temperature distribution inside the heat exchanger. Measurement data are available at the locations indicated in Fig. 3 and these data can be compared to the results of the model.

CONCLUSIONS

The airflow and heat transfer coefficient that were measured during the experiments are quite high for natural convection. The measured air velocity was around 0.8 m/s, whereas the average velocity in the chimney (calculated by closing the heat balance) was around 0.43 m/s. The heat transfer coefficient is measured to be in the range of 25-28 W/m^2K. The efficiency of the heat exchanger at the airside was in the range of 70-80%, which means that the air is heated up to 70-80% of what it could have been in the case of an infinitely long (counter flow) heat exchanger.

The results of the model are in line with the measured values. When the model was run with the measured values for the heat transfer coefficient, the accuracy was 1 – 6%. The model slightly underestimates the temperature of the out flowing air (whereas the temperature of the out flowing water was calculated within 0.5°C).

With the measured and calculated values for the heat transfer and air flow, it should be possible to run the Watergy greenhouse without fans.

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NOMENCLATURE

Q	=	heat flux	[W]
Φ_v	=	volume flow	[m^3/s]
ρ	=	density	[kg/m^3]
C_p	=	specific heat	[J/kgK]
T	=	temperature	[°C]
α	=	heat transfer coefficient	[W/m^2K]
A	=	surface	[m^2]
V	=	volume	[m^3]
k	=	mass transfer coefficient	
λ	=	conduction coefficient	[W/mK]
r	=	heat of vaporisation	[J/kg]
M	=	mass flow	[kg/s]
C	=	air moisture content	[kg moisture/kg dry air]
η	=	efficiency	[%]

Subscripts

as	=	air to solid	s	=	solid
aa	=	air to air	a	=	air
sl	=	solid to liquid	l	=	liquid

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Tables

Table 1. Results of 5 different experiments; cooling at 477 l/s and heating at four different water flows.

	$\theta_{v,l}$ [l/h]	$T_{air\ in}$ [°C]	$T_{air\ out}$ [°C]	$T_{l,in}$ [°C]	$T_{l\ out}$ [°C]	v_{air} [m/s]	$\phi_{v,a}$ [m^3/s]	η [%]	α_{tot} [W/m^2K]
cooling	477.9	33.8	16.2	11.6	17.5	-0.876	-0.171	79	27.7
heating 1	764.9	24.1	42.6	47.1	43.1	0.722	0.173	81	26.4
heating 2	509.3	24.2	41.7	46.0	40.9	0.693	0.159	80	25.5
heating 3	257.6	24.2	41.3	46.4	37.3	0.671	0.146	77	26.4
heating 4	122.2	23.9	40.3	47.2	32.0	0.595	0.120	70	25.2

Table 2. Results of 5 model runs, with the same flows and input variables as the experiments.

	$\theta_{v,l}$ [l/h]	$T_{air\ in}$ [°C]	$T_{air\ out}$ [°C]	$T_{l,\ in}$ [°C]	$T_{l,\ out}$ [°C]
cooling	477.9	33.8	15.6	11.6	18.2
heating 1	764.9	24.1	40.3	47.1	43.2
heating 2	509.3	24.2	39.7	46.0	41.0
heating 3	257.6	24.2	39.7	46.4	37.2
heating 4	122.2	23.9	39.2	47.2	31.5

Figures

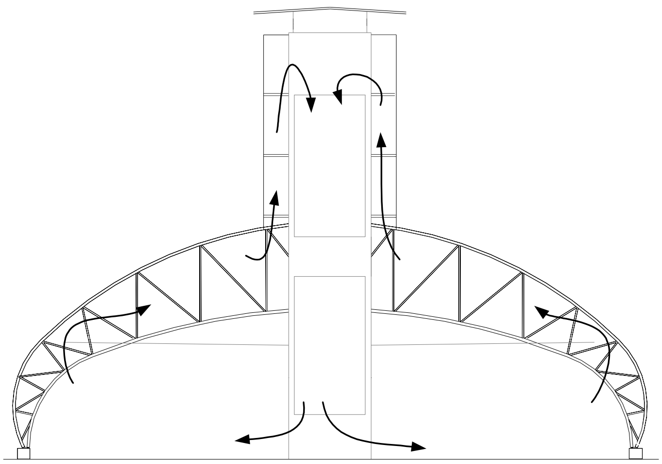

Fig. 1. Airflow in the Watergy greenhouse during the day.

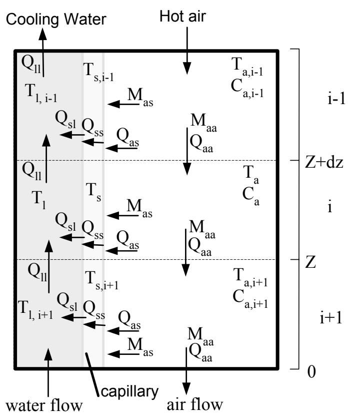

Fig. 2. Model lay out.

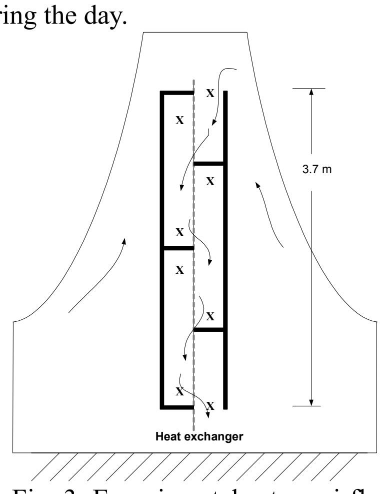

Fig. 3. Experimental setup; airflow in case of air cooling.